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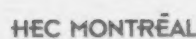
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Planning and Operating a Shared Goods and Passengers On-Demand Rapid Transit System for Sustainable City-Logistics

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Abstract. This paper investigates the potential of integrating in urban areas a shared goods and passengers on-demand rapid transit system. Although persons and goods movements have different objectives and constraints, mixing their travels is within the current trends. In this paper is investigated how they could share a rapid transit network and use more efficiently, in an interconnected way, the available transportation capacity within the city. Based on the common characteristics of Personal Rapid Transit (PRT) and Freight Rapid Transit (FRT), this paper proposes an emergent and efficient transportation solution in order to enhance the sustainability of city logistics. Next, a focus on the operational level is made to characterize the dynamic transportation problem and to propose two strategies to formulate it. This problem aims to respond to a number of transportation requests arriving on a periodic basis, with the adequate service level, while minimizing the empty movements of a restricted set of electric vehicles with limited battery capacity. An efficient solution approach, based on the forward optimization of the periodic transportation sub-problems, is proposed and validated. The applicability of the PRT/FRT mode is demonstrated and computational results in comparison to a classical transportation option is also presented and discussed.

Keywords: City Logistics, interconnected urban transportation, Personal Rapid Transit (PRT), Freight Rapid Transit (FRT), vehicle routing optimization, EV charging.

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1 Introduction

Nowadays, urban areas represent the right place to challenge against climate changes. Cities with their high population concentration, their huge economic activity and their high energy consumption represent the appropriate field to test, develop and promote new transportation technologies and systems.

As reported in [9], urban areas represent only 2% of the world surface and consume more than 70% of the total world resources and generate 75% of the total world waste. In addition, world urbanization trends have seen a significant increase in the recent years, which will probably increase these figures.

Currently, cities' population is becoming bigger than ever, encompassing more than 50% of the worldwide population is living in cities¹, which results on the increase of urban moves for both goods and persons in urban areas. In fact, as the cities expand their size, distributing goods in city centers becomes more complex and harder to manage due to the limited transportation capacity of the urban infrastructure. Passengers' transportation modes have also been considered as one of the huge contributors of greenhouse gas emission and one of the largest consumers of energy[4]. It is estimated that commuting delay to be doubled by 2050 to up to 100 hours² and thus more interconnectivity is needed. Moreover, with the growth of the e-commerce proportion in distribution channels, urban goods'demand tends to become more fragmented than ever with a large number of small packages that need to be delivered to customers' home in shorter time. Accordingly, the last mile delivery problem in urban areas could represent a huge challenge in the near future and must be in the focus form of transportation and logistics managers. From a logistics system perspective, the huge increase in urbanization rate and the change on the people'demands for goods in urban areas, result on many proposals in order to satisfy adequately current and future urban transportation's needs. Different research initiatives and innovative projects have been conducted in the recent years to deal with the sustainability of urban mobility such as CO3³ or the Physical Internet manifesto

¹Source: UN World Urbanization Prospects, World Business Council for Sustainable Development

²Source: UN World Urbanization Prospects, World Business Council for Sustainable Development

³source: <http://www.co3-project.eu/>

[39]. Conceptually, the existing literature considered two ways to deal with all the issues related to urban transportation: develop and enhance the service quality of the already existent transportation modes or design innovative transportation systems that offer an ecological option for urban area stakeholders. The former could be achieved by improving the efficiency of current vehicles in term of transportation's energy usage [33], routes optimization [13] and the increase of the attractiveness of transportation systems [38] via the minimization of carbon emission, traveled distance and/or congestion. The latter, considered in this paper, rely on the promotion of new green transportation solutions ([1] and [56]) and on the proposal of innovative logistics practices such as interconnectivity, collaboration, and sharing. The characteristics of sustainable transportation systems are discussed in [20] and the relationship between sustainability and efficiency in transportation systems is studied in [6] and [17]. Furthermore when looking in general to the existing situation, urban people movements and urban goods movements are rather seen as independent problems. The combination of these two flows is within the recent trends in logistics and transportation systems[10]. In fact, it has been observed recently the emergence of sharing transportation practices where passengers and freights are part of a joint transportation movement or mixed within the same travel [50].

Accordingly, the proposal of this paper is the integration into urban areas of an emerging and sustainable transportation system: the Personal Rapid Transit (PRT) and the Freight Rapid Transit (FRT). It builds also on an interconnected view of all the transportation systems of a given city, and on the usage of sharing practices between passengers and goods movements. PRT and FRT fall into the class of automated transit systems [48] that present an innovative, sustainable and fast way to move both people and goods within urban areas. The PRT and FRT have been introduced by Don Fichter since 1953 [2] and the former have been implemented in many places such as airports (Heathrow Airport, London, UK), hospitals (Hospital Rovisco Pais, Portugal), universities (Morgan Town West Virginia USA) and new ecological cities (Masdar City Abu Dhabi, UAE). A review of existing work on the PRT is found in [12]. However, to best of our knowledge, no proposal of a shared implementation and operation of the PRT and FRT exists. Consequently, planning and operating a shared PRT/FRT mode is studied in this paper in order to estimate the potential of integration of a shared transportation mode in urban areas and its capabilities to improve sustainability. To this end, a dynamic transportation problem is characterized at the opera-

tional decision-making level with the objective to minimize the empty moves of the PRT/FRT mode under service and capacity constraints. Similarities and differences between PRT/FRT transportation problem and the well known vehicle routing problem are studied. Then, to solve the problem a forward periodic-optimization approach is proposed. It relies on a proactive and a reactive strategies to anticipate future demand with vehicles moves in order to provide an enhanced formulation to the problem that allows to solve it efficiently with exact methods. Finally, the transportation solution capabilities are investigated in terms of energy consumption, waiting time and flows capacities.

The paper is organized as follows. Section 2 describes city logistics challenges and presents the PRT and FRT transportation modes and their joint characteristics for an urban usage. Section 3, proposes a novel modeling approach of the problem based two alternative formulations and an efficient solution approach to solve it. In section 4, experiments are designed to evaluate the performance of the solution approach and compare the two proposed strategies for a set of instances with different realistic characteristics. The applicability of the PRT/FRT proposal is demonstrated and computational results in comparison to current transportation alternatives is also presented and discussed. Finally, conclusions and future research directions are provided in Section 5.

2 Integration of the PRT/ FRT mode in urban areas

Earlier, Hesse [22] defined city logistics as the whole transportation flows in urban areas including goods and persons that must be coordinated in order to obtain efficient urban areas. Later on, Taniguchi and Thompson [47] defined city logistics as the process for totally optimizing the logistics and transport activities by private companies with support of advanced information systems in urban areas considering the traffic environment, the traffic congestion, the traffic safety and the energy savings within the framework of market economy. Similarly, Benjelloun and Crainic [7] defined city logistics as the process of systematically solving the problem related to the transfer of freight in urban areas and cities. In the related literature, the surrounding objective of city logistics is the improvement of environmental and societal performance

indicators by the reduction of greenhouse emission, noise and congestion in urban areas and by improving urban life and mobility condition [14] [15]. While trying to reach such objectives, city logistics face numerous challenges that are depicted in Figure 1 and discussed hereafter.



Figure 1: Challenge of city Logistics

In brief, one of the most challenging issue is the congestion that impacts strongly on the quality of transportation services. Dense urban areas that have a high congestion rate on roads are the most exposed. This issue compromises the service level proposed for the last miles delivery, and is considered as a blocking reason for delivering goods and persons just in time [51]. The congestion concern is correlated with rush hours issue, since passengers and goods transportation modes in cities use generally the same infrastructure. As these two distinct flows are not collaborating with each other, they would compete over the limited road capacity in cities [32]. In addition, with the limited road's infrastructure, cities suffer also from limited parking places for both passengers and good transportation modes. From a societal perspective, many private vehicles and delivery trucks proceed with the double parking to overcome the parking limited capacity on cities, which blocks a lane of traffic and prevents having a smooth traffic flow. From an

economic perspective, parking tickets' prices are nowadays very expensive due to the limited available number of parking places and according to [46] could reach 3000\$/month.

Furthermore, Montreuil(2011) [39] raised a critical issue that is the allocation of large load capacity to small volume demands. For instance, in the USA, trucks are only 60% loaded when traveling and larger portions of these 60% are filled with packaging only [40]. This issue could be coupled with the emergence of e-commerce in the last decade which results in a new form of goods demand with higher expectations in terms of service level. Moreover, green logistics deals with garbage, waste, and recycling products from inside to outside the urban areas. In fact, the flows coming to and out of the city are generally managed independently and therefore lack of synchronization. This is another important issue since urban areas are projecting waste much more than it produces goods [11]. For instance, humanity in 2020 will generate more than 1.12 million tons of e-waste [44] and a large portion of it will be generated within urban areas. Finally, creating a sustainable city implies limitations of carbon emission and restrictions of building new infrastructures in favor of building new green and clean zones ([57];[37]) which is also an important issue for city planners.

Based on these challenging issues, we oversee that it could be interesting to come up with an emerging transportation mode that uses electric vehicle and is designed to use a clean, automated and fast transportation system.

2.1 An emerging solution with the PRT and FRT modes

In the last decade, several new transportation vehicles, policies and logistic practices have been proposed to respond to some of the cities challenges addressed above. In this paper, we propose to focus on one of the emerging transportation system, namely the Personal Rapid Transit(PRT) and its equivalent for goods, namely the Freight Rapid Transit (FRT). PRT falls under the class of automated guideway transit systems (AGT) [43] [23]. The PRT uses a driverless technology that proposes to its users a specific transportation transit option where movements are done following point to point transit service. This mode has been compared to the taxi mode where passengers avoid stopping at any unnecessary stations until they reach their destination. The PRT system uses generally, a dedicated infrastructure based on guideways and stations similarly to traditional metro or tramway systems. However, in the PRT case transit is done in small groups (vehicles could take

between 1 to 6 passengers) and directly from any PRT station to another dedicated station thanks to stations positioning that are placed off the main PRT line. Guideways in a PRT system are intended to form a set of joints' loops or a grid, which is different from the traditional rail transportation system (train, metro). The rail network is in a form of line or a corridor whereas the PRT system offers more flexibility with larger destinations choice which is suitable in urban and peri-urban areas.



Figure 2: Example of PRT vehicle

All these unique and specific PRT features combined with the on demand transportation service, and the use of clean energy (electric vehicles), provide a faster, sustainable and attractive transit option. The first ever PRT-like system was operated in Morgan town West Virginia US in the 70's. Recently two PRT systems was operated at Heathrow airport in London and at Masdar City in Abu Dhabi Emirate. Figure 2 depicts two examples of PRT in operation and more specifications on this mode could be found in [35].

The Freight Rapid Transit (FRT) is the equivalent rapid transit system dedicated to freight movement as illustrated in Figure 3a. It shares the same infrastructure and control system than the PRT. The FRT mode uses also small electric driverless vehicles that are designed to transport goods or wastes. These vehicles are designed to take boxes or palettes up to 1200 Kg [36]. FRT mode could benefit from automated loading unloading goods mechanisms and new handling technologies. For instance, Figure 3b depicts a loading operation of an FRT unit which is similar to the one used for transportation freight on air plane.

Based on these common features, PRT and FRT modes have the ability to improve drastically the way people and goods are moved through urban areas. In fact by offering short transit option and small stations and guideways design, PRT and FRT encourage the implementation of walkable, clean and

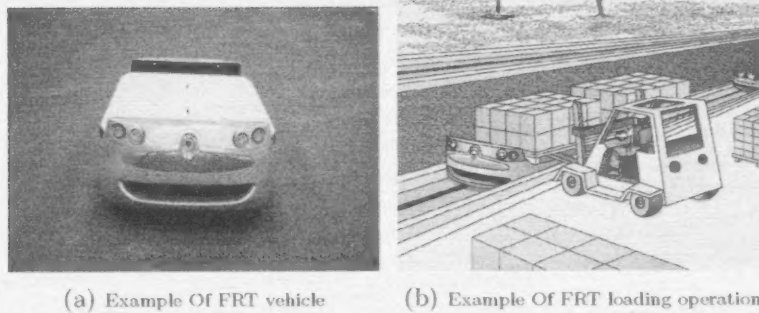


Figure 3: Freight Rapid Transit System

compact areas. The small size of PRT & FRT pods permits its integration into buildings and dense urban zones. In addition, the reduced size of the infrastructure and the stations make the implementation of the system much less expensive than its equivalent train or subway system (estimated to about 60% less than the tramway). PRT and FRT modes are also overseen as one of the best ways to connect urban centers with other nearby sites and peri-urban zones including hospitals, airports, ports, campus, commercial centers, etc. When interconnectivity is possible, it could be a easy system that connects different mass transit systems like trains, aircargo, maritime, etc.

Many studies related to PRT and/or FRT have been focusing on the feasibility and the design of such a system [42], [53], [54], [31]. Recently, focus have been dedicated more to operating issues such as waiting time for passengers [25], [26], [28], [24], [16] and energy consumption [34], [41]. However, to the best of our knowledge, the existing literature have not tackled the possibility to share goods and passengers within the same rapid transit system. Therefore, it will be of high interest to study the possibility of the integration of goods and passengers flows along with PRT and FRT modes in an urban context. The next subsections present our vision to operate a joint transportation mode and interconnect it with existing urban transportation options.

2.2 Shared PRT/FRT-based city logistics approach

Shared transportation systems between goods and passengers flows is within the current trends and the several emerging transportation initiatives.

As an example of using mass transit system to coordinate goods and passengers flows, one could cite the MULI project [52] that uses buses to transport both passengers and small size goods. The E-tram, the cargo tram in Zurich as well as the CarGoTram in Dresden were used as a "goods distribution tool" although passengers were their initial primary use. Shared subway concept was also introduced in many Japanese Dutch and American cities where underground surface were used to move goods during off peak hours. Recently, we should note the share-a-ride problem[30] where it is proposed that goods will be transferred via taxis. Trentini et al [50] proposed a city logistics model that uses a public transportation along with city freighters. The reader is referred to[49] for an extensive literature review on shared transportation practices.

In the same way, this paper proposes a shared PRT and FRT transportation option that could be used to move respectively persons and goods in urban areas. In what follows, we refer to PRT/FRT the integrated transportation mode that is based on the building of a shared network for both modes and on the usage of the PRT or the FRT mode alternatively.

We should note that the PRT and FRT mode could both run independently from each other on specific dedicated infrastructures. However, this solution is according to us behind the moderate success of this mode actually since it comes with extra building and implementation costs. In contrast, sharing the network will increase the utility and decrease the implementation costs associated to this transportation mode. The integration of this new distribution echelon is made possible thanks to the efforts towards building smarter cities with intelligent products⁴ and handling technologies, innovative cross-docking methods (ex: grids) and interconnected information systems.

The illustrative example of Figure 4 depicts an interconnected urban area where the integration of the PRT/FRT mode plays the role of transit/crossdocking for both passengers and goods. Generally, mass transit systems (subways, buses) during off-peak hours have a large available capacity that is simply lost (in term of energy) as mass transit system runs almost empty. Several studies underlined the benefits of using this available capacity to move not only persons but goods from urban centers to the city centers. In the same way, it would be also very interesting to connect the PRT/FRT mode to urban centers and to mass transit stations. Such interconnection

⁴www.ibm.com/smarterplanet/us/en/smarter_cities/overview/

2.3 Characterization of the PRT/FRT decisional problems

Starting from this proposal of PRT/FRT-based interconnected city logistics, its implementation necessitates the consideration of a set of decisions pertaining to three different decision-making levels:

- Strategically, design and build the PRT/FRT infrastructure (guide-ways itinerary, stations and depots location), under city regulation constraints and budget limits.
- Periodically (seasons, months, weeks) schedule the time windows for the PRT/FRT usage and allocate the number of vehicles, under demand fulfillment policies and congestion constraints.
- On a daily basis, optimize the transportation problem of the PRT/FRT moves for each time window under waiting time, battery and capacity constraints.

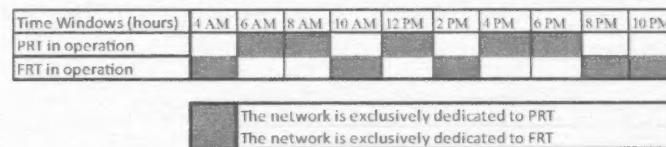


Figure 5: Daily Planning example of PRT/FRT mode into a set of Time windows .

Accordingly, this paper assumes that all the decisions related to the design of the PRT/FRT infrastructure are already made and that a PRT/FRT network is already implemented within an urban area. Moreover, it assumes that the periodic scheduling of the network usage is set and it gives a known partition of each working day into a set of time windows (TW). Each TW

specifies if the network is allocated to the PRT, to the FRT or to both of them simultaneously. Figure 5 provides an example of such daily planning where the shared network is dedicated for each TW whether to the PRT or to the FRT. The example of Figure 5 illustrates a system operational during 20 hours per day partitioned into a set of TWs of 2 hours length each. Depending on the behavior of the demand and the dynamic of the city context, the TWs length could be increased or decreased accordingly without further complications. For instance, during the rush hours, the entire network will typically be scheduled to run the PRT mode exclusively along the corresponding TW and no other traffic will be allowed. On the other hand, during off peak hours, the system will be scheduled alternatively to operate the PRT or the FRT flows to meet the passengers or goods transportation needs. Otherwise (the first and last TWs), priority will be given to the goods transportation service. We could note as an example that night delivery option with trucks were experimented successfully in many cities such as Barcelona⁵, Dublin, etc. The typical scheduling case described here seems the more realistic and will be the one considered for the rest of the paper. Note that considering the specific case, where both PRT and FRT could move simultaneously, does not alter the modeling and solution approach employed hereafter⁶.

For a given TW, the running mode (PRT or FRT) have to meet the upcoming demand that is generally characterized by a poisson arrival process. The granularity of the periods within a TW must be defined with the appropriate granularity (ex: 1 minute or 5 minutes) to shape more precisely the arrival process of demand. For each TW, two alternative modes of operation⁷ could be distinguished : the on-schedule mode and the on-demand mode:

- On-Schedule mode: when the demand of passengers/goods is highly predictable, the PRT/FRT moves could be anticipated to run on a fixed set of origin-destination demand pairs according to a preset schedule.
- On-Demand mode: when the demand arrival is not scheduled or is not predictable, the system operates under uncertainty, and must run on a dynamic set of origin-destination demand pairs according to occurring demand.

⁵www.civitas.eu

⁶This specific case necessitates the modeling of a multi-commodity formulation of the proposed models.

⁷See for instance the Morgantown PRT system: <http://transportation.wvu.edu/r/download/18440>

The on-schedule mode corresponds to the deterministic case and could be useful also for dealing with PRT in rush hours or FRT when goods moves are predictable (or a priori booked) for a pair of origin-destination. This mode is in fact a specific case of the on-demand mode of operation that underlines the high dynamics of demand and the associated transportation problem. Thus, in what follows, the problem modeling and the solution approach will tackle the general case of on-demand mode. According to this characterization of the PRT/FRT decisional problems, we focus in what follows on the dynamic PRT/FRT transportation problem that minimizes the empty vehicles movements along a given TW under on-demand mode. Recently, for a dedicated PRT system Lccs-Miller[24], Lccs-Millers and Wilson [29] [27], Daszczuk et al. [16] studied to minimize the waiting time for passengers under stochastic demand but without considering battery issue for PRT vehicles. Mrad and Hidri [34] and Mrad et al. [41] considered a similar routing problem for a un-capacitated PRT operating under a deterministic context. To the best of our knowledge, the FRT counterpart was not inspected and the dynamic setting of the PRT/FRT problem was not studied. This work extends these recent studies by characterizing the on-demand mode of operation, modeling the related dynamic transportation problem and applying it to the PRT/FRT mode in urban areas.

3 The Dynamic PRT/FRT Transportation problem

In this section, we focus on the on-demand mode of the PRT/FRT transportation problem with the aim to minimize the movement of empty vehicles and the waiting time of passengers/goods request in a dynamic context. As underlined previously, both economic and sustainability performances are desired in city logistics context and thus are considered in the model hereafter. In fact, determining which vehicle to move and where to move it is known as the empty vehicle redistribution (EVR) problem for PRT systems ([26] and [28]). In the dynamic case, operating the PRT/FRT mode along time can result in a high level of unused capacity due to empty vehicles moving between stations when responding to passengers/goods demand. This issue is made more challenging in this paper by considering the use of electric PRT vehicles with limited battery capacity. When batteries capacity is limited, this cause

additional empty vehicle movements to recharge the vehicles batteries at the network depot.

Furthermore, the PRT/FRT dynamic problem shares some characteristics with the dynamic one-to-one pickup and delivery problem. As Berbeglia et al. [8] suggested, the dynamic one-to-one pickup and delivery problem can be partitioned into three subcategories:

- When vehicles can serve more than one request at a time, we have the classic dynamic pickup and delivery problem.
- When the transportation request consists of passengers as in a bus system, we have the dial-a-ride problem.
- When the vehicle can perform only one request at a time, we have the stacker crane problem.

As we shall see, our problem is close to the last case and presents the same complexity level than the stacker crane problem. Thus, our modeling approach takes benefits from existing characterization of the dynamic one-to-one pickup and delivery problem. For a more detailed review on this problem, see [45]. Moreover, to solve efficiently this complex problem a forward periodic-optimization approach is developed. It builds on two strategies to formulate the problem using linear programming techniques which enhances its solvability with exact methods. The dynamic matching strategy (DMS) refers to the reactive EVR approach, and the fixed vehicle number strategy (FVNS) refers to the proactive EVR approach. On the next, we define the dynamic PRT/FRT transportation problem and presents the two formulations, and then, describes the overall solution approach.

3.1 Definition and modeling

To start with, let us examine the business context of the PRT/FRT system more closely. A PRT/FRT system contains a set of homogeneous PRT and FRT vehicles that offers to its customers a specific on-demand transportation service from a departure station to a destination station of the PRT/FRT network. A transportation request is assumed to be either a single or group of passengers for the PRT case and a palette or a set of parcels of goods for the FRT case. One or more transportation requests arise from the various stations of the network at the same time. The PRT/FRT system must then

dispatch and send different vehicles to the pickup point of each transportation request in order to satisfy it. The various transportation requests received along the time windows of the day differs by their specific characteristics (number of passengers, weight of the palette, etc.) which impacts on the load capacity and the energy consumption of vehicles.

For a given time window (see Figure 6), the continuous arrival of transportation requests is shaped by a discrete set of periods in which PRT/FRT mode demands are received incrementally. For each period, the PRT/FRT decision support system must decide which request to serve first and which vehicles need to be moved at minimum cost. When transportation requests are served, a vehicle need either to stay at its current position or to return to the depot to recharge the battery. For a given PRT/FRT network considered, a cost is associated to the decision of assigning a specific vehicle to a transportation request. This cost is composed of the energy used by the vehicle to satisfy the request as well as the time that the transportation request will be waiting to be served. To model the PRT/FRT transportation problem, the following assumptions are stated :

- The PRT/FRT network has enough guideways to make it possible to move between any pair of stations.
- The distance between each pair of stations (i, j) on the PRT/FRT network is calculated using the Floyd-Warshall algorithm[19].
- We suppose given the cost matrix *Cost* which represents the cost incurred in terms of the energy used when a vehicle is moved between a pair of stations.
- The PRT/FRT system includes a fixed set of vehicles VH . Each vehicle $v_i \in VH$ has a battery of capacity B . The vehicles can only recharge their batteries in the depot. VS_i denotes the station in which vehicle v_i is located.
- The passengers/goods requests are gradually received over time, and we assume there is no stochastic information about the incoming rate of transportation requests.
- We assumed neglectable the loading and unloading operations duration for passengers and goods.

For a given TW, the time evolution is indexed by a discrete variable $\tau \in [0, \tau_{max}]$. Initially, at $\tau = 0$, all the vehicles are in the depot and have full batteries. When a passenger or goods transportation request p_i is received, it is defined by the following characteristics:

- Departure station DS_i
- Arrival station AS_i

At the beginning of each period $\tau > 0$, the PRT/FRT vehicles will be either:

- idle at a station.
- idle at the depot.
- charging at the depot.
- moving empty to pick up a transportation request.
- taking a passenger/good request to his destination.

As we discretized the time horizon, a decision has to be made at each period τ based on the new state of the system. These periodic decisions are made independently from future periods and doesn't change the previous period decisions. However, for a given period τ , the state of the network is updated based on the set of decisions made previously. More specifically, in addition to the newly arriving demand, the system takes into account all the remaining unserved demand at previous periods. Also, the system considers an updated state of the vehicles locations and the batteries levels. Figure 6 illustrates this dynamic setting by underlying the propagation of the system state from time period τ to time period $\tau + 1$. It also depicts with uplinks from each period to the subsequent one, the system update in terms of vehicles location, charge and remaining requests.

According to this periodic updating process, at the beginning of period τ , the set of considered demand is denoted by d_τ . At the end of the period, when decisions are revealed, the set of non satisfied demand for period τ is known and is denoted by \bar{d}_τ . Therefore, at the subsequent period $\tau + 1$, the upcoming demand $d_{\tau+1}$ is composed by \bar{d}_τ augmented by the newly received demand, denoted by $\bar{d}_{\tau+1}$. As shown in Figure 6, at $\tau = 0$, the PRT/FRT decision support system will need to respond to new requests by dispatching

vehicles to them. As a result, the set of the new demands at $\tau = 0$ will be divided into a set of satisfied demands and a set of unsatisfied demands. Unsatisfied demand for a given period is due to limited fleet size and/or battery capacity constraints. The set of unsatisfied demands will have to wait until the subsequent period (ex: $\tau = 1$) where the PRT/FRT control system will consider them in the optimization process. As illustrated, at period $\tau = 1$ for instance, the vehicles status is also updated based on the decisions made at $\tau = 0$. The set of new empty vehicles includes vehicles arrived to their destinations and vehicles that finished their charging at the depot. Obviously, when each periodic decisions set depends on information up to time τ , this further complicate the solution approach. A similar "offline" strategy has been applied to solve the Real-time multi-vehicle truckload pickup and delivery problem in [55].

In this paper, in order to minimize the total empty movements by period, two strategies are considered to formulate the optimization problem at each time period τ .

1. The dynamic matching strategy which is a reactive strategy that moves vehicles on reaction to the current state of the system.
2. The fixed vehicle number strategy which is a proactive strategy that moves vehicles proactively while predicting future moves of the PRT/FRT vehicles.

In the next section, we give an overview of a first developed strategy called dynamic matching strategy.

3.2 The dynamic matching strategy

In this section, we introduce the dynamic matching strategy to the periodic optimization problem which is inspired from the concept of game theory [18]. It consists on having for the PRT/FRT transportation problem two set of agents: The PRT/FRT vehicles and the transportation requests (either goods or passengers demands). The transportation of vehicles from their current location to the transportation request's location is costly (in term of empty moves). Consequently, the main objective of our strategy is then to minimize the transportation cost of empty vehicles from departure to arrival station while offering a good quality service. To optimize this objective, we use a cooperative approach between the available vehicles on the network

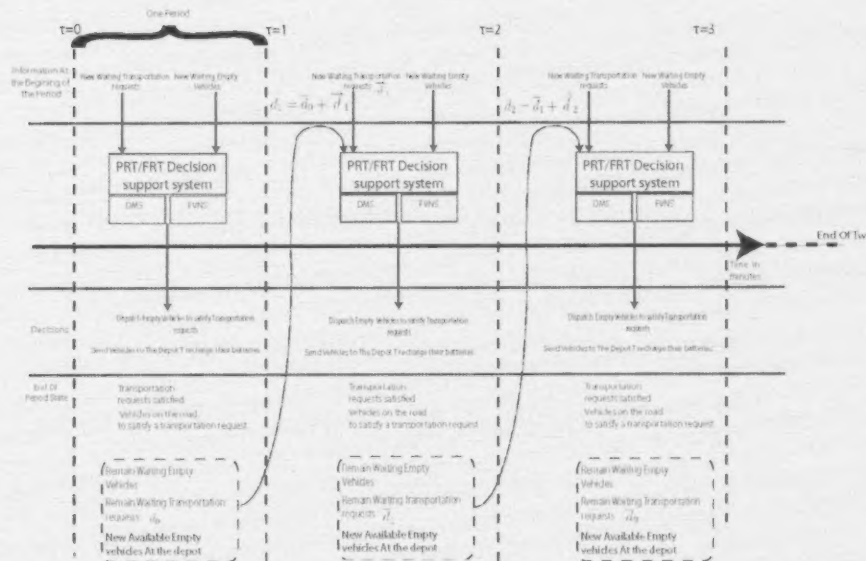


Figure 6: Overview of the system over a set of periods in the time window

which promote the good distribution of vehicles while respecting their battery capacities. Accordingly, the dynamic matching strategy (DMS) move idle vehicles reactively according to passenger/good's requests. The main idea is to solve, at each time period, an assignment problem taking into account the actual state of the system.

For this purpose, we define a bipartite graph $G = \{\vec{V}, \vec{E}\}$ (Figure 7), where:

- \vec{V} is formed by two disjoint subsets S and T .
- S is the set of nodes s_i , where each node represents a free vehicle v_i in any station of the network. We add to this set a dummy node dp that represents all vehicles that are available in the depot. Let $S^* = S \setminus dp$ be a partition of S .
- T is the set of nodes t_j in which each node represents a passenger/good j waiting for a vehicle.

- We denote by Bt_i the remaining energy in the battery of vehicle v_i at time τ .

The set of edges E is defined by the following rules:

- For each pair of nodes (s_i, t_j) , where $s_i \in S^*$, we add an arc (i, j) only if $Bt_i \leq Cost(VS_i, DS_j) + Cost(DS_j, AS_j) + Cost(AS_j, D)$.

This condition will ensure that each vehicle v_i can move to the demand arrival station and travel to the desired destination, while keeping enough energy level to return to the depot for charging the battery. For the arc (i, j) is associated a cost denoted by $Cost(VS_i, DS_j)$.

- For all nodes in T , we add an arc (dp, t_j) that has cost denoted by $Cost(D, DS_j)$.

One should notice that graph G is unbalanced, because we have $|S| \neq |T|$, and is not complete. The problem of finding a minimum cost for assigning a vehicle to a request can be viewed as the minimum cost matching problem in an unbalanced bipartite incomplete graph.

We could transform G to a complete balanced graph by adding enough dummy nodes and edges, but this would increase the size of the problem and decrease the performance of the algorithm. To eliminate unfeasible matchings, we do as follow:

- We decided to add only one dummy node dn to the set T .
- For each node in S , we add to the set \vec{E} an arc (s_i, dn) with a very large cost denoted M (i.e. a big number).
- We also define set $T^* = T/dn$.

A usual approach to solve the matching problem in graph G is to transform it to a flow problem. For this purpose:

- We add two dummy nodes d_s and d_t .
- For each node in S , we add an arc (d_s, s_i) with cost 0.
- For each node in T , we add an arc (t_i, d_t) with cost 0.

From this graph representation, illustrated in Figure 7, we could get two main general structures:

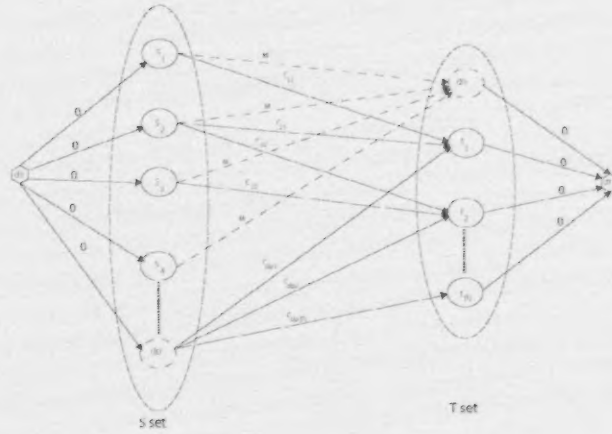


Figure 7: Graph construction for the DMS at a given period τ

- a case where $|S| \leq |T|$.
- a case where $|S| > |T|$.

As our problem is solved at each time period in a dynamic context, we need a very quick and responsive solution procedure to get good quality solutions in a very short time. To do so, we developed two flow-based formulations of the assignment problem based on the cardinality of sets S and T .

We first introduce the following integer variable:

$$x_{ij} = \begin{cases} 1 & \text{if arc } (i,j) \text{ is selected to match } i \text{ to } j \\ 0 & \text{otherwise} \end{cases}$$

Let us also define:

- $\delta^+(i)$ is the set of edges that have i as a root.
- $\delta^-(i)$ is the set of edges that have i as a sink.

If $|S| < |T|$, we solve the following linear program:

$$\text{PRT/FRT(11):} \quad \text{Minimize} \quad \sum_{(i,j) \in E} \text{Cost}_{ij} x_{ij} \quad (1)$$

$$\sum_{j \in \delta^+(i)} x_{ij} = 1 \quad \forall i \in S^* \quad (2)$$

$$\sum_{j \in \delta^-(i)} x_{ji} \leq 1 \quad \forall i \in T^* \quad (3)$$

Otherwise, we solve the following linear program:

$$\text{PRT/FRT(12):} \quad \text{Minimize} \quad \sum_{(i,j) \in E} \text{Cost}_{ij} x_{ij} \quad (4)$$

$$\sum_{j \in \delta^+(i)} x_{ij} \leq 1 \quad \forall i \in S^* \quad (5)$$

$$\sum_{j \in \delta^-(i)} x_{ji} = 1 \quad \forall i \in T^* \quad (6)$$

Objectives (1) and (4) aim to minimize the total cost used to assign all trips.

Constraints (2) and (6) require that each node must be in the final solution exactly once.

Constraints (5) and (8) require that each node may or may not be in the final solution.

Based on the cardinality of sets T and S , solving these models will assign each transportation request an idle vehicle to satisfy their request. In case of there are not enough vehicles, a first-in first-served policy is applied such as the passengers/goods with the highest waiting time will be served first.

3.3 The fixed vehicle number strategy

In this section, is proposed an alternative strategy called the fixed vehicle number strategy (FVNS) which aims to reduce the energy consumption in a PRT/FRT system. FVNS is based on the principle that each station should have a fixed number of vehicles waiting to take passengers/goods all times. If a station has fewer waiting vehicles than required, empty vehicles are moved to that station to satisfy this need. The basic idea of maintaining a fixed number of vehicles waiting idle at a station has been treated by different studies in the PRT literature, such as [5], [3], and [28]. We extend this

strategy to the specific context of a PRT/FRT system under vehicles battery constraints.

First let us recall that a departure station is denoted by DS_i and an arrival station is denoted by AS_i for a given request p_i . The following additional notations are needed to define the FVNS formulation :

- Let ρ be the index that denotes a given station in the network.
- Let ϑ_ρ be the number of vehicles waiting at station ρ .
- Let ϕ_ρ be the number of vehicles moving around the network for which station ρ is the destination,
- Let ψ_ρ be the number of passengers/goods requests waiting at station ρ .
- Let θ_ρ be the number of vehicles that should be located at a station ρ .

For each station ρ , we could have two situations:

- If $\vartheta_\rho + \phi_\rho - \psi_\rho > \theta_\rho$, then station ρ has a surplus of vehicles, σ_ρ^+ .
- If $\vartheta_\rho + \phi_\rho - \psi_\rho < \theta_\rho$, then station ρ has a deficit of vehicles, σ_ρ^- .

To eliminate this latter deficit, we proceed as in the previous section by modeling and solving a network flow problem.

For this purpose, we define a bipartite graph $\Gamma = \{\vec{V}, \vec{E}\}$ where:

- \vec{V} is the set of nodes that contains two disjoint sets S and T .
- S^* is a partition of set S . To construct S^* , we consider vehicles present at a station with a surplus. Then, we add a node s_i to the set S^* for each surplus vehicle j , choosing the vehicles with the highest remaining energy level in their batteries. For example, if station 5 has a surplus of two vehicles, we add two nodes to S^* representing the two vehicles that have the highest level of energy among those present at station 5.
- We add to the set S^* a dummy node dp to represent all available vehicles at the depot.
- We note that $S = S^* \cup dp$.

To build the set T , we consider only the stations with a deficit of vehicles. For each of those stations ρ , we add a node t_ρ .

To construct the set of edges E , we use the following rules:

- for each pair of nodes (s_i, t_j) , where $s_i \in S^*$, we add an arc (i, j) only if $Bti \leq Cost(Station(s_i), t_j) + Cost(t_j, D) + (reserve)$. This condition ensures that each vehicle v_i can travel to the station, serve a potential passenger/good request through the *reserve* energy, and then return to the depot for charging. The arc (i, j) will have a cost denoted by $Cost(Station(s_i), t_j)$. The reserve parameter ensures that a given vehicle has enough energy to satisfy a probable upcoming request and then return back to the depot for recharge. If a vehicle would not ensure to have this reserve energy the arc will not exist.
- for the node dp , we add θ_ρ arcs (dp, t_ρ) that have the cost $Cost(D, t_j)$.

This graph Γ is also a bipartite graph. We proceed as in the previous section, by transforming our problem into a network flow problem:

- We add two dummy nodes d_s and d_t to the graph.
- For each node in S , we add an arc (d_s, s_i) with cost 0.
- For each node in T , we add an arc (t_i, d_t) with cost 0.

At each time τ , we construct the graph Γ based on the state of the PRT/FRT system, and then solve the following linear program:

We first define the variable y_{ij} as

$$y_{ij} = \begin{cases} 1 & \text{if arc } (i, j) \text{ is selected to match } i \text{ to } j \\ 0 & \text{otherwise} \end{cases}$$

$$\text{PRT/FRT(21):} \quad \text{Minimize } \sum_{(i,j) \in E} Cost_{ij} y_{ij} \quad (7)$$

$$\sum_{j \in \delta^+(i)} y_{ij} \leq 1 \quad \forall i \in S^* \quad (8)$$

$$\sum_{j \in \delta^-(i)} y_{ji} = \sigma_i^- \quad \forall i \in T \quad (9)$$

where σ_i^- is the deficit at node i (i.e. station). Objective (7) aims to minimize the total cost of eliminating the deficit at all stations.

Constraint (8) requires that each vehicle should move to satisfy at most one station's need.

Constraint (9) requires that each station can receive the necessary number of empty vehicles. Contrary to equations (5) and (6), we apply Constraint (9) to all nodes in set T as set T in the FVNS strategy doesn't have a dummy node. Therefore, its principle of sending vehicles to stations could be applied to all the present nodes representing the stations.

Solving this mathematical formulation will assign a target station to each vehicle represented in the set S . To assign passengers/goods to a vehicle, we use a simple first-in first-out strategy where passengers/goods with the the longest waiting time will be served by the nearest vehicle with a feasible energy level.

Using this strategy and after assigning and moving vehicles proactively to guarantee the availability of free vehicles in each station, the FVNS assigns vehicles to transportation requests using a simple First In First Out rule. In fact, following the actual state of the system (the location of free vehicles and the location of transportation request), the decision support system will assign the nearest available vehicle to the transportation request that have enough electric charge. This in combination with the proactive movements of the vehicles could enhance the performance of our system. We should note that the initialization phase of this strategy considers to assign automatically from the depot θ_ρ vehicles for each station ρ .

3.4 Solution approach

To synthesize the solution approach developed to solve the dynamic PRT/FRT transportation problem, a generic schema is provided in algorithm 1. Recall that it relies on a forward periodic-optimization approach applied along each time window of the operational level. This schema underlines how the decision-support system acts periodically to optimize the assignment problem at each time period taking into consideration an updated state of the system (the waiting transportation request, the location of each vehicle, etc). It mentions also how the DMS and FVNS strategies are employed to make periodic dispatching decisions efficiently for the PRT/FRT vehicles.

Algorithm 1 Pseudocode of the PRT/FRT system over time

```

1: Initialization Phase
2: while  $\tau < \text{Max Time}$  do
3:   Receive New transportation requests
4:    $d_\tau = d_{\tau-1} + \bar{d}_{\tau+1}$  { //The set of transportation demand is equal to the new coming transportation demand in addition to the old transportation demand resulted from the previous period. }
5:   Check New Vehicles that finished their charging process in the depot { // We shall now update the state of each vehicle in the system according to the period  $\tau$  }
6:   for all Vehicles:  $v_i \in VH$  do
7:     Check Empty Vehicle  $v_i$  that arrived to its destination and update its status
8:     if true then
9:       Set  $v_i$  State to Free
10:    end if
11:    Check Vehicle  $v_i$  that arrived to its destination to take transportation request
12:    if true then
13:       $v_i$  Pickup transportation request
14:    end if
15:    Check Vehicle  $v_i$  that arrived to its destination to dropoff transportation request
16:    if true then
17:       $v_i$  dropoff transportation request
18:      Set vehicle  $v_i$  State to free
19:    end if
20:  end for
21:  Use a strategy to assign empty vehicles to waiting transportation requests
22:  if Chosen Strategy is DMS then
23:    Construct Graph
24:    Apply the Mathematical Model
25:    Assign Vehicle to transportation requests
26:  end if
27:  if Chosen Strategy is FVNS then
28:    Construct Graph
29:    Apply the Mathematical Model
30:    Assign Vehicle to Stations
31:    Assign Vehicle to transportation requests
32:  end if { //After obtaining the set of decisions from the strategies, we shall now send vehicles to serve their assigned transportation request }
33:  Update state of vehicles
34:  for all Vehicles:  $v_i \in VH$  do
35:    if  $v_i$  has been assigned a transportation request then
36:      Check Vehicle that is already in the departure station of its assigned transportation request
37:      if true then
38:        Pickup transportation request
39:      else
40:        Send Vehicle to the departure station of its assigned transportation request
41:      end if
42:    end if
43:  end for
44:  for all transportation requests  $\Theta$  in the system do
45:    if  $\Theta$  has not been assigned a vehicle then
46:      add  $\Theta$  to  $d_\tau$ 
47:    end if
48:  end for
49: end while

```

4 Simulation and computational results

This section is dedicated to the validation of the solution approach proposed (algorithm 1) to solve the dynamic PRT/FRT transportation problem and to the comparison between the reactive and proactive strategies proposed. In addition, a comparative analysis of the economic and ecologic performances between the PRT/FRT transportation mode and a traditional road transportation option is provided.

4.1 Plan of experiments

In order to validate our solution approach on a realistic PRT/FRT city logistics context, we used, the Corby PRT network. It is obtained from the ATS/CityMobil software which is a PRT network design and simulation tool⁸. The Corby PRT network, illustrated in Figure 8, is a realistic case study developed by Bly and Teycheene [48]. Corby is a town in Northampton, (UK) with a population of approximately 50 000. It offers a good example for testing the feasibility of rapid transit solution in a relatively new town. The original network has 15 stations and four depots. This network comprises 14.2 km of oneway guideways where the mean demand-weighted passengers trip distance is about 3.8 km. The ATS/CityMobil software provides the demand matrix that represents morning peak for the first phase of the Corby network, as used previously in [25]. For this network, the ATS/CityMobil tool provides also a distance matrix that represents the shortest distance between each pair of stations.

Based on this original case, we generated a large set of instances to cover a wide spectrum of realistic city contexts. These instances were generated based on the following three dimensions: Demand scenario, network topology and fleet size:

- Demand scenario: to obtain different plausible scenarios, traveling requests from any station i to station j were generated according to a Poisson process with rate $\lambda_{ij} \in [0.789, 17.902]$. These rates are publicly available in the ATS/CityMobil software and are given the ATS/CityMobil software (see Figure 9). We generated randomly 30 distinct scenarios along the TW horizon (i.e. $\tau \in [0, 120]$ minutes⁹).

⁸ATS/CityMobil PRT source: <http://www.ultraprt.com/prt/implementation/simulation/>

⁹This was done using the Anylogic simulation Software (www.anylogic.com). Further

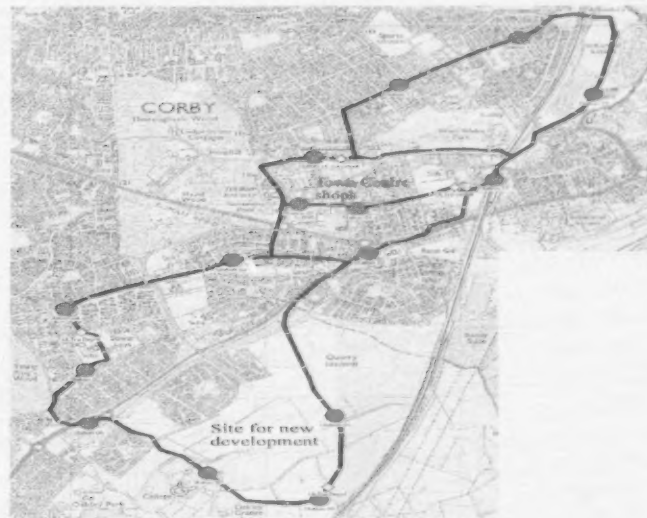


Figure 8: The Corby Network

- Network topology: our aim is to consider a much constrained network than the original Corby network with only one depot available instead of four. For this reason, we duplicated the Corby network four times and selected in each replication one different depot location among the four available initially. As it can be seen in Figure 8, the four depots are in the North East, North West, South East, South West of the network. Using this dimension in our tests is of a high importance since vehicles will need to return periodically to the depot to charge their battery.
- Fleet size: we used three cases including 100, 200 and 300 vehicles to study the impact of the vehicles availability on the waiting time. We note that in our case the electric vehicles battery capacity was supposed to be very tight and was fixed to 40 minutes (which corresponds to only 33% of the time window length). Also, in the FVNS strategy the *reserve* parameter is fixed to s equal to 10% of the battery capacity B .

Therefore, the combination of these three dimensions yields a total of 360 instances. Each instance is characterized by a triplet (ω, ξ, ζ) where explanations are given in Appendix A

	Station 01	Station 02	Station 03	Station 04	Station 05	Station 06	Station 07	Station 08	Station 09	Station 10	Station 11	Station 12	Station 13	Station 14	Station 15
Station 01	0	0.8	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 02	0.8	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 03	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 04	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 05	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 06	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 07	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 08	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Station 09	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1
Station 10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1
Station 11	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1	0.1
Station 12	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1	0.1
Station 13	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0.1
Station 14	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1
Station 15	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0

Figure 9: Origin-destination arrival rates matrix

$\omega \in \{1, 2, \dots, 30\}$ for the demand scenarios, $\xi \in \{100, 200, 300\}$ for the fleet sizes and $\zeta \in \{1, 2, 3, 4\}$ for the network topologies.

The solution approach proposed in this paper (Figure 7) was implemented in C++ language using Visual Studio 2008. The experiments were performed on a computer with a 3.2 GHZ CPU and 8 GB of RAM. We should note that calibration tests were performed for the FVNS strategy and are presented in Appendix B. We note also that all the mathematical models were solved using IBM-Cplex 12.2 commercial solver on the same computer. The time limit parameter of the solver was set to 50 seconds in order to guarantee a solution before the end of the period (recall that we fixed each period length to 1 minute). Our calibration tests shown that, thanks to the enhanced formulation of the problem and the efficiency of the solver, this time limit was sufficient in all the instances to obtain the optimal solution¹⁰.

4.2 Numerical Results

Given the 360 problem instances specified previously, this section discusses the performance of the solution approach with both strategies in terms of the average waiting time and the percentage of wasted energy. Table 1 reports the simulation results obtained for each strategy. The average waiting time represents the total waiting time for all the transportation requests cumulated until $\tau = 120$ minutes (i.e. end of the TW), which is divided by the total number of served requests. The wasting energy for a TW represents the total energy used for empty moved cumulated at $\tau = 120$ minutes, divided by the total energy consumption. As shown in Table 1, the two strategies produce good performance regarding the mean waiting time with an aver-

¹⁰The MIP size is ranging from 50 to 300 in terms of binary variables and from 10 to 60 in terms of constraints.

age of about 4 minutes which is less than alternative public transportation modes. Globally, DMS performs always better than the FVNS and presents a more conservative behavior. On average DMS is slightly better than FVNS and the standard-deviation of the former is also better. Conversely, thanks to its high performance variability, FVNS produces the best minimum and 25% percentile evaluation. Also, the worst case in terms of average waiting time is given by the FVNS. Regarding the wasting energy performance, DMS outperforms FVNS, which means that the reactive approach employed in the former better resolve the EVR problem. However, in these results one should underline that FVNS produces more stable solutions in term of wasted energy over the different scenarios as it gives the lowest standard deviation with 4.327%. Further statistical results comparing the performance of both strategies are provided in Appendix C.

Table 1: Descriptive statistics for the results of the mean waiting time of transportation requests in minutes

Statistic	DMS		FVNS	
	Mean Waiting Time in min	Wasting Energy in %	Mean Waiting Time in min	Wasting Energy in %
Minimum	2.604	36.54	1.86	41.64
25% Percentile	3.493	48.56	2.436	53.36
Median	3.937	53.09	3.019	56.72
75% Percentile	4.679	57.46	6.313	59.07
Maximum	6.72	65.68	9.674	66.94
Mean	4.124	52.63	4.21	56.21
Std. Deviation	0.8295	6.065	2.253	4.327

Furthermore, the set of Figures 10a,10b,11a,11b,12a and 12b shows the behavior of these strategies performances according to the three dimensions studied in the problem instances. The average waiting time curves illustrate an overlap between DMS and FVNS performance when the network topology (Figure 10a), the scenario (Figure 11a) or the fleet size (Figure 12a) dimension is inspected. On the other hand, when looking to the wasting energy performance, Figures 10b, 11b and 12b confirm the dominance of DMS compared to FVNS, respectively on the three dimensions. As it can be seen from these figures, the performance of the DMS is much better than the FVNS as it presents lower or at least equal waiting times and wasted energy than FVNS in the majority of the instances.

Another interesting results observed is that both strategies have the same behavior on the different scenarios, which underline the stability of the entire solution approach although the dynamic setting of the problem. We mention

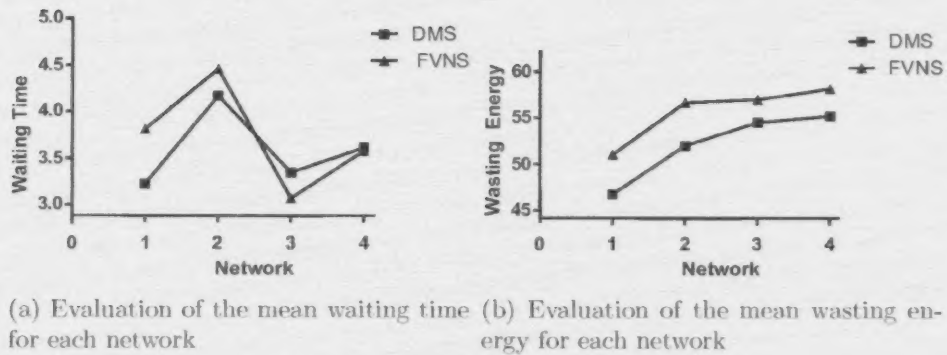


Figure 10: Pictures of Grouped Analysis for each Network

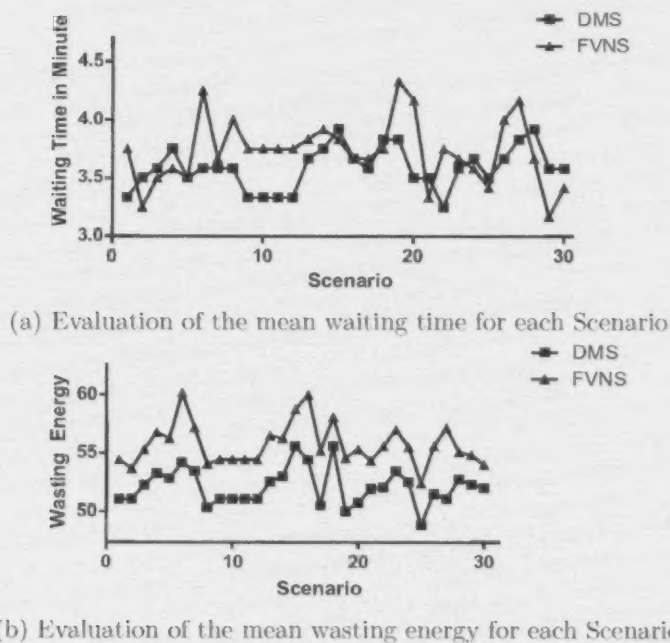


Figure 11: Pictures of Grouped Analysis for each Scenario

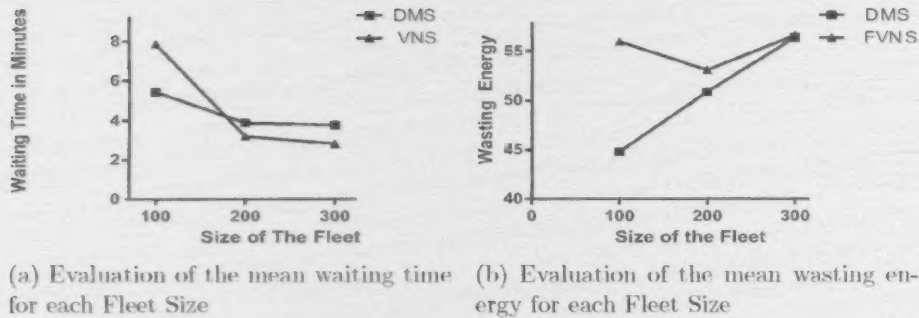


Figure 12: Pictures of Grouped Analysis for each Fleet Size

that the largest gap between the two strategies occurs at scenario 27 (about 6 %) and the smallest gap occurs in scenario 30 (about 2%) in favor of DMS. We can also see that FVNS tends to extend the empty moves made by idle vehicles when few passengers are arriving. In fact, the FVNS could result in long empty moves for vehicles arriving from the depot, as they have a high energy level to recalibrate the number of idle vehicles in each station. By solving a matching problem at each time period, DMS is able to manage the system more efficiently. Vehicles were generally moved to their nearest point of demand, and therefore there is a small number of empty movements with this strategy. Conversely, while considering the number of passengers/goods requests at each station, FVNS is able to prioritize stations with larger vehicle deficits over those with small deficits. For example, if a station has a large deficit of vehicles, the associated node in the matching problem graph will have more arcs, and will therefore be prioritized over stations with a smaller deficit. Finally, the obtained results show the effectiveness of our two strategies, as they were able to minimize the mean waiting time and the movement of empty vehicles. However, the sensitivity of these results to the network topology underlines the importance of the depot location in the PRT/FRT network. Recall, that we reduced from four to one, the number of depots existing in the original Corby network. This seems to impact negatively on the wasting energy criterion ranging in average between 40% and 60%. Accordingly, drastic improvements of the empty vehicles moves should be reached by increasing the number of depots in the PRT/FRT network or using a depot location optimization approach.

4.3 Comparative analysis

This last subsection is dedicated to a preliminary comparison of our city logistics proposal integrating a PRT/FRT mode with a more classical transportation system employing taxis/trucks to deliver passengers or goods, respectively.

This last subsection is dedicated to a preliminary comparison of our city logistics proposal integrating a PRT/FRT mode with a more classical transportation system employing taxis/trucks to deliver passengers or goods, respectively. To do so, we used as benchmark the Corby network presented above. For the pickup and dropoff locations in the classical transportation mode, we assumed that these are located at the stations coordinates in the Corby network. Given that, two cases are investigated :

To do so, we used as benchmark the Corby network presented above. For the pickup and dropoff locations in the classical transportation mode, we assumed that these are located at the stations coordinates in the Corby network. Given that, two cases are investigated :

- Case A where classical transportation mode follows exactly the same route as the PRT/FRT network guideways, which means keeping the same distance matrix.
- Case B where the classical transportation mode follows the shortest path between each pair of stations in the city, which means re-estimating the distance matrix of the modified Corby network.

For the latter case , contrary to PRT/FRT mode, we considered two ways roads which would simulate more realistic urban conditions. Also, we modified the shape of the distance between each couple of stations to follow traditional roads on the ATS/CityMobil software. In addition, we considered the impact of congestion factor on urban areas. To do this, we assumed that a truckload in an urban area has an average speed of 35km/h [21] due to congestion, limited speed and city regulations. Then, as the size of the fleet of vehicles increases the congestion of the roads would increase too, which is reflected on the average speed by a decrease of 5km/h as the size of the fleet was increased by 100 vehicles. Regarding the demand scenarios, we kept the same poisson process and the same number of scenarios as in the previous experiments. The instances generation procedure is explained in details in Appendix A.

Therefore, the combination of all of these parameters yields a total of 720 instances. Each instance is characterized by a quintuplets $(\omega, \xi, \zeta, \iota, \varrho)$ where $\omega \in \{1, 2, \dots, 30\}$ demand scenarios, $\xi \in \{100, 200, 300\}$ for fleet sizes, $\zeta \in \{1, 2, 3, 4\}$ for network topologies, $\iota \in \{1, 2\}$ transportation modes compared and $\varrho \in \{35, 30, 25\}$ for average speed values.

As for the previous experiments, the loading and unloading times are supposed neglectable in these tests. To compare the PRT/FRT and the traditional transportation systems on the energy consumption, the following assumptions are added: i) we estimated that a PRT/FRT system has an average energy consumption of 0.18kWh/km¹¹; ii) we estimated that one Gasoline Gallon Equivalent is equal to 33.40 kWh¹²; iii) we estimated that the average energy consumption for traditional transportation system is 30 miles per gallon¹³.

Then, for each scenario we generated the relative energy consumption of each system expressed in Gasoline Gallon Equivalent. Comparison between the PRT/FRT energy consumption and traditional transportation system was assessed using the following formula expressing the gap in energy consumption:

$$GAP = \left(\frac{W(TT) - W(RT)}{W(TT)} \right) * 100 \quad (10)$$

Where $W(TT)$ and $W(RT)$ denotes the performance in average energy consumption (in Gallon) for the traditional transportation mode (TT) and the PRT/FRT mode (RT), respectively. We note also that in these additional tests, the same solution approach was applied while relaxing the battery capacity constraints in the mathematical model. We solved each instance using IBM-Cplex 12.2 and results were expressed in term of total time used to satisfy the total transportation requests. The results are synthesized in Table 2 based on the gain made by the PRT/FRT mode in terms of consumed energy depending on the fleet size, the network case and the average speed.

First, we should note that these tests prove that our modeling approach and solution method could be generalized to solve any dynamic transportation problem, not only PRT/FRT case. Second, the obtained results confirm

¹¹source:<http://www.advancedtransit.org/advanced-transit/comparison/prt-characteristics/>

¹²source:Electricity Prices by State - National Electric Rate Information. Eisenbach Consulting, LLC.

¹³source:National Highway Traffic Safety Administration. "Summary of Fuel Economy Performance".

Table 2: Comparative results between PRT/FRT and traditional transportation modes

Size of Fleet	Network	Average Speed in Km/h	Gain in term of consumed energy in %
100	Case A	35	66.633
100	Case B	35	42.435
200	Case A	30	67.089
200	Case B	30	43.391
300	Case A	25	67.406
300	Case B	25	32.289

the superiority at the operational level of our PRT/FRT city logistics proposal in comparison with a traditional transportation system. The PRT/FRT system uses less energy to satisfy the same transportation requests. On average the difference of gain reaches about 53%. The gain increases slightly with the size of fleet, due to the negative impact of congestion on the traditional transportation mode. Regarding the inspection of Case A and Case B of the network structure, the gain is better in the former case (i.e., when the same routes are used by both modes) with about 67% rather than 32% with 300 vehicles, for instance. Such gains are also explained by the higher speed of the PRT/FRT mode that is not constrained by congestion in urban areas.

Moreover, the gain could be accentuated when the CO₂ emissions of the two solutions are inspected. In fact, the PRT/FRT solution was estimated to generated on average between 0.018 and 0.023 gCO₂/passenger per km¹⁴.

In conclusion, we could underline from these results that PRT/FRT mode offers many advantages : i) the reduction of the travel time due to its higher speed; ii) reduction and relief of congestion as many of the urban traffic would be moved to the PRT/FRT network; and iii) reduction of the energy consumption and carbon emissions as the PRT/FRT is of a much smaller size than other traditional transportation tools and uses electric vehicles.

5 Conclusion

Personal rapid transit and freight rapid transit are part of an emerging transportation mode that aim to offer a high quality transportation service to its users. This is possible by using driverless electric vehicles that could trans-

¹⁴source:<http://www.advancedtransit.org/advanced-transit/comparison/prt-characteristics/>

port persons or alternatively goods with a food service level and in a sustainable way. In this paper, we considered a possible application of the PRT/FRT mode by proposing a shared network of both persons and goods into an integrated proposal in order to enhance urban mobility. The proposal builds on the possible interconnection of this novel mode with existing mass transit tools like bus or subways. The characterization of the decision problems highlighted the importance and the complexity at the operational level to solve the dynamic PRT/FRT transportation problem. This problem aims to minimize the total energy consumption and the waiting time for transportation requests under limited battery capacity. For this dynamic problem, an efficient solution approach was proposed, encompassing two strategies for solving by optimization the periodic empty vehicle redistribution problem. These strategies formulate and solve a maximum matching problem in an unbalanced graph, which enhanced the problem resolution.

The solution approach was tested on a large set of instances, based on a realistic test case of the Corby network. The experiments made showed that the solution approach proposed provides good results in terms of solution quality and solution time. We found that DMS is superior to FVNS in terms of effective energy consumption thanks to its reactive empty vehicle redistribution strategy. In addition, these results showed the potential gain of implementing the PRT/FRT mode compared to the current transportation options in terms of waiting time and wasting energy. These results are a first insight to show the benefit of the PRT/FRT mode and further experiments are necessary on various city logistics contexts. Also, the two strategies examined could be refined to further improve the wasting energy performance. Furthermore, the modeling approach and the solution method could be tested in other transportation problems under dynamic setting. Finally, the incorporation of ride-sharing concepts, waste logistics issue, and smart technologies for cross-docking, loading/unloading operations could be interesting to investigate in an urban context.

A Generation of the Test Instances

To generate the test scenarios, we used the data already provided in the ATS/City Mobile software while including it into the Anylogic software. The Anylogic software is a powerful Java Based simulation tool that have the possibility to simulate different process using different simulation tools such

as discrete event simulation, system dynamic and agent based process. To generate our different scenarios we proceeded as follow:

1. Under Anylogic, we created a Java class "Scenario generation" that contains the matrix of lambda rates as a static member.
2. We create an active object "station" that simulate the process of arriving of transportation requests(see Figure 13). The "station" active object have different source objects that simulate the arriving process from a specific station to another station.
3. As we have 15 stations in the Corby Network, we duplicate in the main class 15 occurrence of the "station" active object while changing at each time the parameter of the origin station for each active object (see Figure 14).
4. Finally, we run our simulator program and the arriving process were recorded into a scenario file that was used as part of our C++ simulator for testing our two strategies.

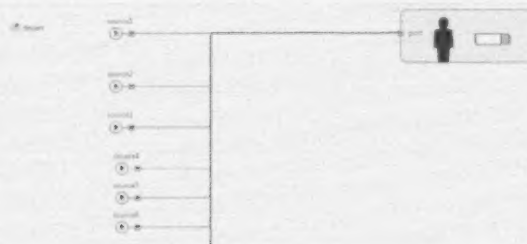


Figure 13: Overview of the Active Object

B Calibration of the FVNS approach

FVNS includes a parameter that states how many vehicles should be present at each station. In this section, we study the effect of varying this parameter. We fix the number of vehicles to 200 PRT/FRT pods, and test the 20 generated scenarios with parameter values from 1 to 8. Table 3 presents the results of this study. Figure 16a shows the effect of varying the parameter on

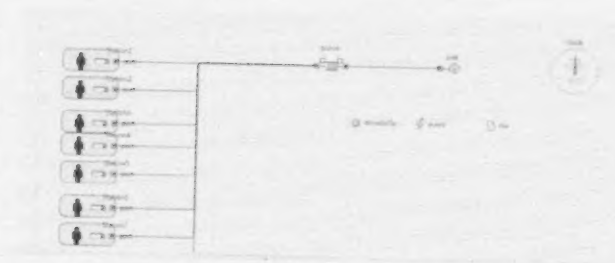


Figure 14: Overview of the Main Class

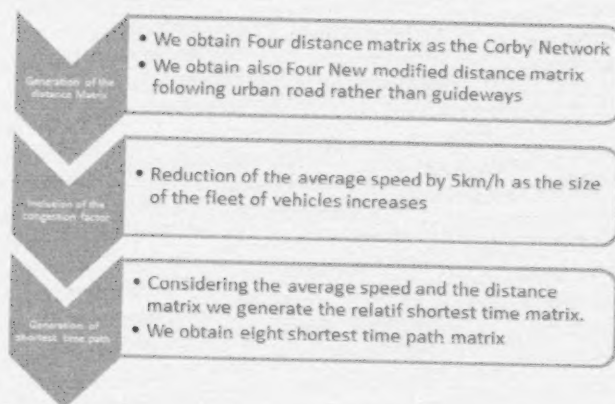


Figure 15: Process of the generation of the Comparison instances

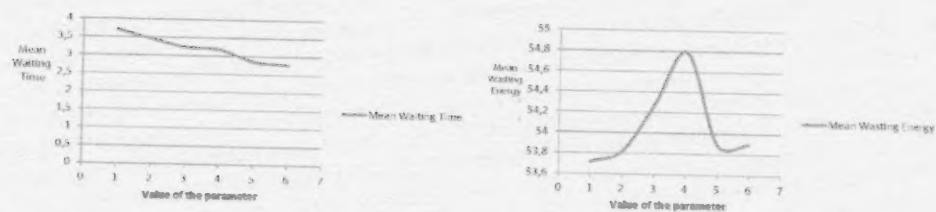


Figure 16: Effect of the parameter on the FVNS

Table 3: Results of the Calibration of the fixed number of vehicles in FVNS

Parameter	Mean Waiting Time min	Mean Wasting Energy %	Gap Waiting Time	Gap Wasting Energy
1	3.7	53.712		
2	3.45	53.816	-0.245	0.103
3	3.233	54.272	-0.224	0.456
4	3.172	54.789	-0.061	0.517
5	2.851	53.890	-0.321	-0.899
6	2.770	53.899	-0.081	0.009
7	2.438	52.429	-0.331	-1.469
8	2.233	51.592	-0.205	-0.837

the mean passenger waiting time. Figure 16b shows the effect of varying the parameter on the empty displacement of vehicles. These results show that varying the number of vehicles at each station has a significant effect on the waiting time. In fact, the mean waiting time is negatively correlated with this parameter. However, increasing the value of this parameter increases the amount of wasted energy. Once the parameter is greater than 4, the wasted energy decreases. This can be explained by the fact that, with five vehicles waiting in each station, passenger demands can be satisfied without long waiting times and wasted energy. From this study, we can conclude that having five vehicles waiting is the best value for our strategies, as it presents a good trade-off between the waste of energy and the passenger waiting time. We could see from the gap value in Table 3 that reaching the value of 5 we get a stabilization on the results as the gap decrease significantly to reach -0.081 Waiting Time and 0.009 for the Wasting Energy.

C Statistical Analysis of the results

For further comparison between our two strategies, we performed a *t*-test for correlated samples within the different observations. We conducted two *t*-tests to check whether the differences in waiting times and effective energy are significant. Tables 4 and 5 show the results of the two *t*-test conducted in this study.

The *P*-value for the waiting time is 0.3024, which means there is no significant difference between our two strategies in terms of waiting time. Therefore, we can conclude that DMS as well as the FVNS performs equally in terms of passenger/goods waiting times. For the effective energy, we get a *P*-value of less than 0.0001, which shows that the probability that the difference in effective energies was caused by chance coincidence is less than

0.0001. From our comparative analysis, we can claim that DMS is better than FVNS in terms of effective energy consumption.

Table 4: Results of the t-test for the mean waiting time

P value	0,3024
Significantly different? ($P < 0.05$)	No
One- or two-tailed P value?	Two-tailed
t, df	t=1,033 df=359
Number of pairs	360
How big is the difference?	
Mean of differences	0.08564
SD of differences	1.573
SEM of differences	0.08293
95% confidence interval	-0.07745 to 0.2487
R square	0,002962

Table 5: Results of the t-test for the empty displacement of vehicles

P value	< 0,0001
Significantly different? ($P < 0.05$)	Yes
One- or two-tailed P value?	Two-tailed
t, df	t=12,89 df=359
Number of pairs	360
How big is the difference?	
Mean of differences	3.585
SD of differences	5.278
SEM of differences	0.2782
95% confidence interval	3.038 to 4.132
R square	0,3163

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